Broadband Seismic Characterization of the Arabian Shield

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Abstract

We propose to carry out a field program in the Kingdom of Saudi Arabia to collect a suite of broadband seismic waveform data and the associated parametric data describing the sources. We plan to deploy 6 portable broadband seismic stations along 3 profiles on the Arabia Shield and record over a period of about a year. Most of the regional seismic sources will be in the tectonically active area of Iran and Turkey to the northeast. Other areas of seismic activity include the Red Sea Rift bordering the Shield to the southwest, and the Dead Sea Transform fault zone to the north.

In addition to data recorded at the portable stations, we will also utilize other broadband data sources in the region including GSETT-3 stations, GSN stations, and other seismic facilities in Central Asia. All data collected in the course of this program will be organized in version 3.0 CSS databases and be available for distribution.

The main research objectives of the proposed program are:

1. to study the propagation of regional phases across the Arabian Shield over a broad band of frequencies,

2. to study the crustal structure and seismicity of the Arabian Shield, and

3. to characterize potential sites for permanent seismic facility installation

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Background and Collaboration

The Arabian Peninsula presents several interesting seismological problems. On the west, rifting in the Red Sea has split a large Precambrian shield, the Arabian Shield, into two distinct parts (see Figure 1). The geometry of the Arabian Plate is well-outlined by teleseismic epicenters (see Figure 2). Active rifting is responsible for the geometry of the plate margins in the west, and southwest. To the south, similar rifting running in a more east-west direction through the Gulf of Aden has separated the Arabian Peninsula from Africa. In the northwest, the Gulf of Aqaba forms the southernmost continuation of the Dead Sea transform. The northern and northeastern boundaries of the Arabian Plate are areas of continental collision, with the Arabian Plate colliding with the Persian Plate. The overall lack of seismicity in the interior of the Arabian Plate, though not as absolute as might be thought from Figure 2, suggests that little internal deformation of the plate is presently occurring.

There has only been a modest amount of earthquake seismological work done in the Arabian Peninsula. Several countries either on or surrounding the Peninsula have seismograph stations, but most stations are equipped only with short-period vertical seismometers. In any event, the networks are sparse and often are poorly situated with respect to active areas. Surface wave dispersion studies and explosion studies have defined crustal structure in the oil-producing areas adjacent to the Persian Gulf and along a transect of the southern part of the Arabian Shield, but only gross features of crustal structure are known in most of the Peninsula. Broadband data required for analysis of teleseismic receiver functions are almost wholly lacking. Regional wave propagation from earthquakes and seismic wave attenuation have not been studied. Microseismicity is known to occur in many areas of the Peninsula, but the existing network of stations is inadequate for accurately defining spatial characteristics or determining focal mechanisms.

We propose to address several of these problems by a program of broadband seismic monitoring in Saudi Arabia, in cooperation with Saudi scientists. For many years the Kingdom has been very "closed" to all but a few joint projects. In fact, one cannot even visit the country without written invitation by a Saudi official. We are very fortunate in having obtained Saudi government permission for this field program from Dr. Mohammed Al- Suwaiyel, the Vice President for Research of the King Abdul Aziz City for Science and Technology (KACST), the government agency responsible, by Royal decree, for seismological studies in the Kingdom. This will be the first joint US-Saudi field program in seismology for many years and, we hope, represents a new openness of the Kingdom for such joint works. This joint program will be carried out under the aegis of the King Saud University (KSU).

Structure of the Arabian Shield

The Arabian Shield consists of a large outcrop of Precambrian rocks in the western Arabian Peninsula (see Figure 2). The Red Sea rift has separated similar rocks which outcrop in Egypt and the Sudan. Rocks of the shield are highly variegated (U. S. Geological Survey and Arabian American Oil Company, 1963). Although granite and gneiss do not dominate the exposed rocks, there are large outcrop areas of both. Cenozoic basalts overly shield rocks in some areas (Figure 2). On the west, shield rocks are bordered by Cenozoic deposits of the Red Sea coastal plain, including volcanics from a number of late Quaternary vents. On the east, shield rocks are bordered by sedimentary rocks of the Arabian platform. Three principal Precambrian tectonic provinces have been

distinguished in the area of the shield lying generally south of latitude 24 degrees North (Greenwood et al., 1980).

A USGS velocity profile was run across the Arabian Shield from near Riyadh to the Red Sea in 1978 (Mooney et al., 1985). To first order, the Arabian shield consists of two layers, each about 20 km thick. Average velocities are 6.3 and 7.0 km/sec, respectively. The depth to the Moho averages about 40 km, thinning slightly from northwest to southeast. The upper mantle velocity is 8.0 - 8.2 km/sec. Based on surface wave dispersion studies using regional WWSSN-type stations, the Mooney et al. model is a reasonable approximation to crustal structure throughout the Arabian Shield (Mokhtar et al., 1992).

Mooney et al. suggest that the geology and velocity structure of the shield can be explained by a model in which the shield developed in the Precambrian by suturing of island arcs. Mooney et al. interpret the boundary between the eastern shield and the Arabian Platform as a suture zone between crustal blocks of differing composition. Prodehl (1985) noted that the upper crust of the eastern shield appears to be more uniform than that of the western shield. Mooney et al. note that mapped gneiss domes correlate with high velocity bodies in the upper crust.

The record sections shown by Mooney et al. (1985) and their interpretations indicate that crustal phases such as P_n and P_mP are well-recorded to distances of at least 300 km. Intracrustal reflectors were also observed, which were interpreted as coming off the tops of bodies of mafic intrusives.

There is differing information on the attenuation structure of shield rocks. Short-period Rayleigh waves along the USGS line suggest Q of 400 to 700 for the upper igneous rocks at depths of 500 m or so (Mokhtar et al., 1988). Badri (1989), from the P waves recorded on the USGS profile, found that Q_p for P_g ranges from 50 to 850 in the shield. Qp for the Pn phase averaged 1075. On the other hand, H. Ghalib's studies of regional attenuation of the L_g phase suggest much lower values of Q, around 150-250 (personal communication, 1992). Shield areas of most parts of the world are associated with generally high Q values, and the interpreted velocities from the refraction profile would also suggest that Q should be moderate to high. All studies that could distinguish between Arabian Shield and Arabian Platform propagation paths found that velocities were lower and attenuation higher in the platform.

Seismo-tectonics of the Arabian Peninsula

Dead Sea Transform

The Dead Sea transform system connects active spreading centers of the Red Sea to the area where the Arabian plate is converging in southern Turkey (see, e. g., Dewey et al., 1973). The transform fault system dates from the Middle Cenozoic and is primarily a left-lateral feature (Nur and Ben-Avraham, 1978). Over 100 km of sinistral motion is estimated to have occurred on the system (Quennel, 1958; Freund et al., 1970). The southern portion of the rift system is the Gulf of Aqaba. Both strike-slip and normal faulting occur in the Gulf of Aqaba in connection with the formation of en-echelon rhombic-shaped grabens (Al-amri et al., 1991).

Seismicity of the Dead Sea transform is moderately high. A magnitude 6 1/4 earthquake occurred in Jordan in 1927. About 800 events of magnitude 1.5 to 4.6 have been located in the Gulf of Aqaba by the King Saud University seismic network between October

1986 and March 1990 (Dr. Abdullah Al-amri, personal communication, 1994). More recently, magnitude 6.0 and 5.7 events occurred on 3 August 1993.

Red Sea Rift

The Red Sea Rift is the dominant tectonic feature of western Arabia. The Red Sea's axial rift developed in the Pliocene in a pre-existing depression (Girdler and Styles, 1974). It connects the Dead Sea transform to the Afar triple rift junction in eastern Africa. Continued active rifting is indicated by the high rate of seismicity in the Red Sea. A magnitude 7.1 event occurred in the northernmost Red Sea near the mouth of the Gulf of Aqaba in 1969, and a magnitude 5.8 event occurred on 13 March 1993 in the central Red Sea, south of Jiddah. There are many NE-trending transform faults along the Red Sea (Whiteman, 1970) and some of these may extend into the western Arabian Peninsula.

Gulf of Aden

The plate boundary extends east-northeast from the Afar region through the Gulf of Aden and into the Arabian Sea. The boundary is clearly delineated by teleseismic epicenters (Figure 2), although there are fewer epicenters bounding the eastern third of the Arabian Plate south of Oman.

The Zagros Folded Belt

The Arabian Plate is bounded along its entire northeastern length by the Zagros folded belt, a continental collision zone with the Persian Plate. Most seismicity appears to occur in the crustal part of the Arabian Plate beneath the Zagros folded belt (Jackson and Fitch, 1981). The Zagros is a prolific source of large magnitude earthquakes, with numerous magnitude 7+ events occurring in the last few decades.

Arabian Plate Interior

The interior of the Arabian Plate is generally marked by very low levels of seismicity. This is not merely an effect of poor network coverage; operation of the King Saud University seismic network indicates that microearthquake activity generally originates in the same areas as the teleseismically-located events. In the western Peninsula, however, there are some areas of enhanced seismicity that are unquestionably on land. The 1982 North Yemen earthquake (Langer et al., 1987) is the best-known recent earthquake to occur on the Arabian Peninsula, having resulted in about 3,000 fatalities. This magnitude 6 event was caused by normal faulting (Choy and Kind, 1987). At least 3 other magnitude 5 1/2 to 6 1/4 events are known from the Asir region of southwestern Saudi Arabia between 1941 and 1965. Microearthquake investigations have demonstrated seismicity in the Asir area (Merghelani and Gallanthine, 1980), and the King Saud University telemetry network has occasionally located events there (Altan Necioglu, personal communication, 1993). Farther to the north along the Red Sea, on-land seismicity is known from the Yanbu region of northwestern Saudi Arabia (Merghelani, 1981) and in the Makkah-Taif region (Merghelani et al., 1981). Seismicity in the Makkah-Taif region may be associated with a northeast-trending mapped fault.

The causes of this intraplate seismicity are not well understood. There is widespread Quaternary volcanism along the Red Sea coast, with at least one documented historical eruption in 1256 A. D. Some seismicity was associated with that eruption. Seismicity may also be related to transform faults in the Red Sea continuing onto land, as well as other causes. To date, few on-land epicenters are accurately located and there are few focal mechanisms available.

A large earthquake (magnitude 6.6) is shown on the seismicity map (Figure 2) in the plate interior along the Iraq-Saudi Arabia border. This earthquake occurred in 1953, but we know little about it.

Deployment Plan

We have a plan to operate 6 portable broadband seismographs at a minimum of 9 sites in the Arabian Shield. Our planned deployment is shown in Figure 3. The triangular pattern will insure that seismic wave characteristics over a large area of the Shield will be assessed for a wide variety of sources, and that there will be a tie-in to previous refraction seismology studies in the shield.

The first deployment will consist of 3 seismographs in the area of the proposed GSN station at Ar Rayn near Riyadh. The remaining 3 units will be deployed at existing sites along an east-west profile from Daharan through Riyadh to Makkah.

We then plan to move the 3 units deployed around Ar Rayn along the 1978 USGS profile line, running from just west of Riyadh to Asir Province near the Red Sea Coast in the southwest. The profile's long axis is pointed in the direction of high seismicity in the Zagros. These earthquakes are occurring in the Arabian Plate where it is colliding with Persian Plate (Jackson and Fitch, 1981). Seismic wave ray paths along this profile from Zagros events should therefore have entirely intra-plate paths. Stations will be between 900 and 1500 km from the nearest Zagros sources, although existing broadband and long-period stations not located on the Arabian Shield are closer (350 to 700 km). Events in the highly active area of the Afar triple junction in Africa are also generally aligned with the deployment.

The array deployments will allow sampling of regional wave characteristics over a broad area, from very numerous source regions. It is reasonable to expect that ray paths traversing virtually every area of the shield will be recorded, given the high seismicity rates characteristic of most of the active areas around the shield. We expect from experience operating portable seismographs in some parts of the shield that most sites will have very low noise levels, so a variety of teleseismic signals suitable for receiver function analysis should also be obtained.

Instrumentation and Installation Methods

Each station will have a Streckeisen STS-2 broadband seismometer which has a pass band between 0.008 Hz and 100 Hz. Each seismometer will be heavily insulated to protect it from the daily changes in temperature. We have successfully run STS-2 seismometers in a desert environment during the summer of 1992. These sensors were deployed for the Landers earthquake aftershock experiment in the Mojave Desert in southern California. Each sensor will be attached to bedrock outcrops whenever possible.

The output of the STS-2 will normally be recorded at a sample rate of 40 sps by a 24-bit REFTEK RT72A-08 datalogger. At the station the data will be stored on a 1 Gbyte SCSI disk. To take advantage of the copious amounts of sunshine available in Saudi Arabia, we will use solar panels to charge car batteries. Timing to the station will be provided by a local GPS clock. This will avoid the problem of any potential leap second changes. Data will be retrieved by exchanging disks at each site during service runs. Each site will need to be visited on a monthly basis.

RESEARCH PRODUCTS

CSS Databases

Operating at 40 samples/second continuously, each station will collect 41.5 Mbytes of waveform data per day. Thus, about 250 Mbytes per day for the 6 stations will have to be processed. Assuming that there will be the equivalent of about 300 network-days of operation during the experiment, the total data produced will be on the order of 75 Gbytes.

All data gathered from the portable stations (and some data from other sources) will "packaged" into a version 3.0 CSS databases. These databases will include one containing all waveforms with the continuous data segmented into some convenient epochal length and the associated station descriptive data will be stored in the *site, sitechan, sensor*, and *instrument* relations. Another database will contain segmented waveforms containing seismic signals and information on these signals and their sources, stored in the *origin, assoc,* and *arrival* relations. These databases will be available for distribution with the final report.

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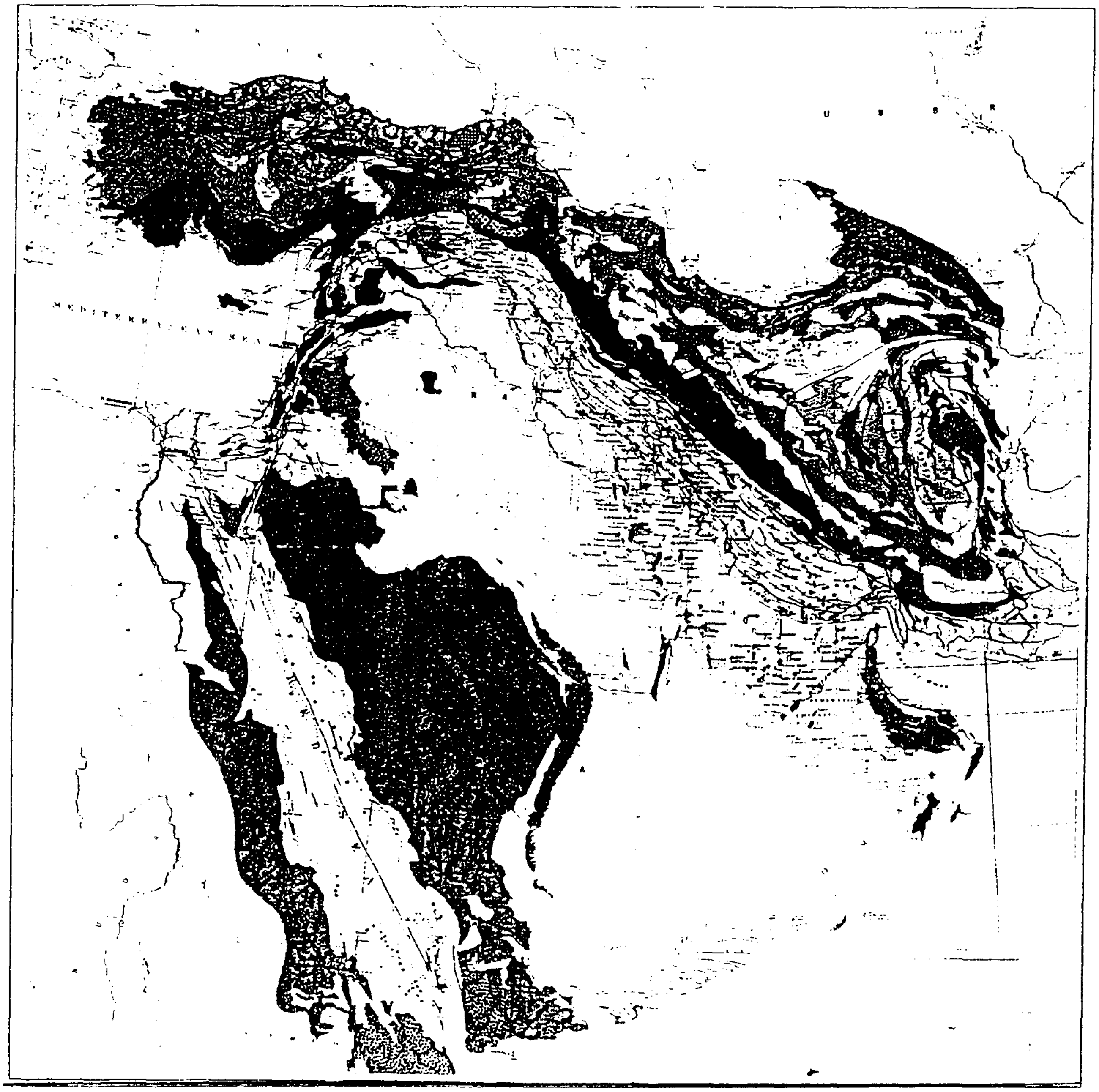

Figure 1. Map of the Arabian Peninsula area, adapted from tectonic map produced by Petroconsultants (1977). Lightly stippled area shows extent of Precambrian shield rocks on both sides of the Red Sea. Darkly stippled areas are shield areas covered by Quaternary basalts.

Mb >= 4.0 Events at Regional Distances from Saudi Arabia

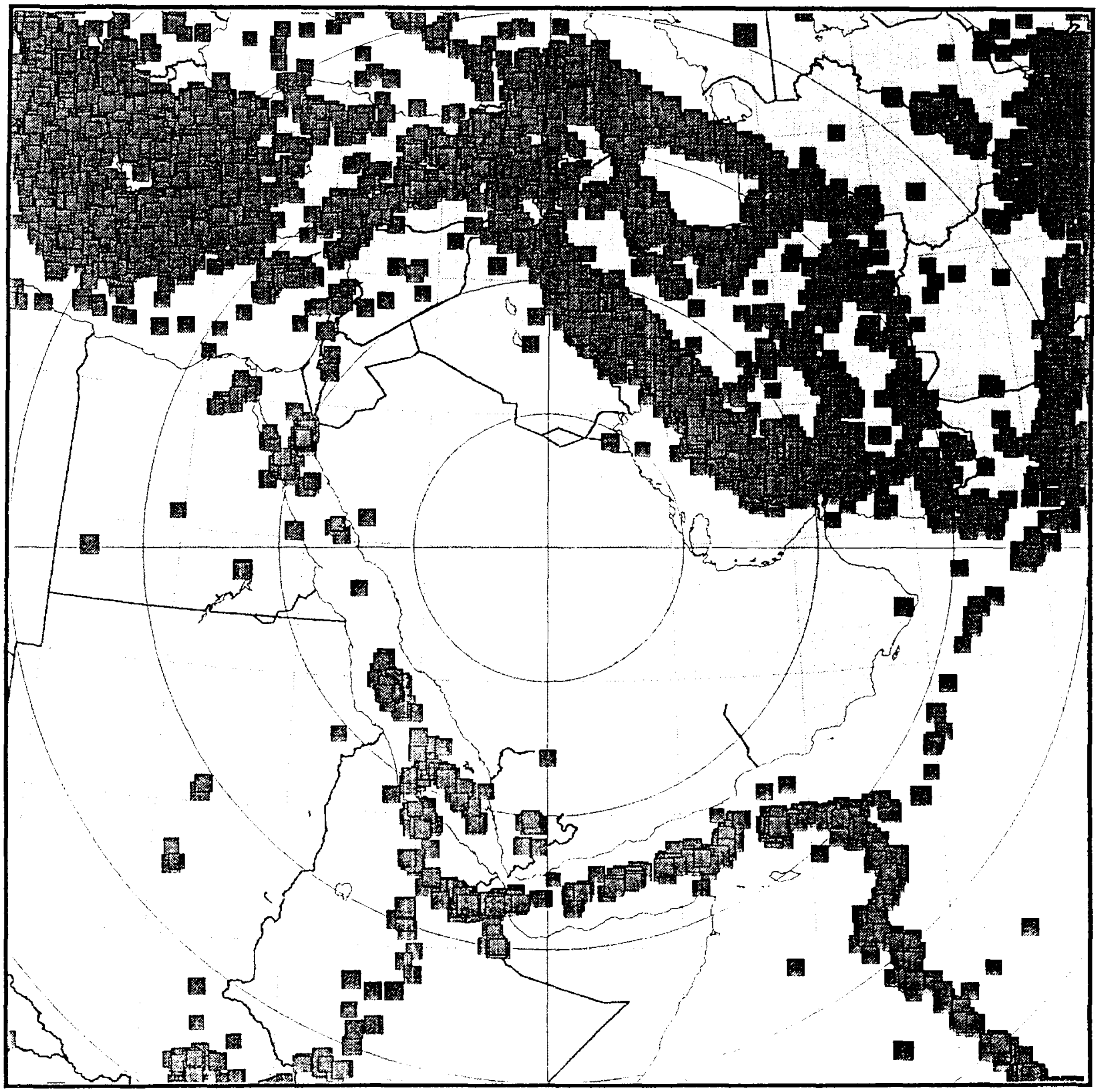

Figure 2. Seismicity of the Arabian Peninsula area, taken from the PDE data base. Map shows events with magnitude greater than 4.0 since 1966.

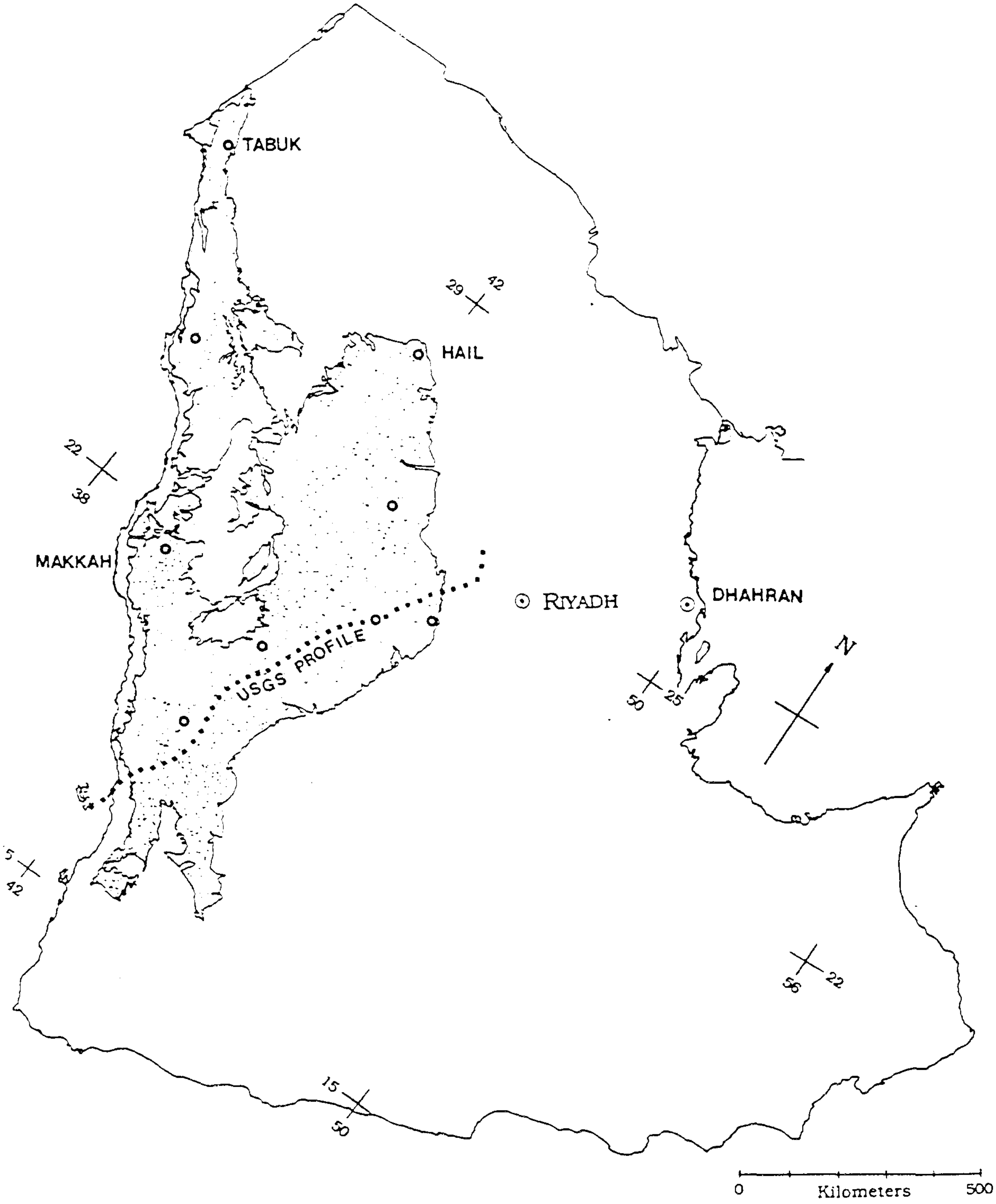

Figure 3. Planned broadband station deployment (small circles). Lightly stippled area is Arabian Shield; Quaternary lava cover within the shield is not stippled. In the first phase of our deployment, the four stations along the USGS profile and at Hail and Makkah would be operated. In the second phase, the four stations along the Red Sea coast and the 4 running along the northeast edge of the shield would be occupied. 6-component stations exist at Riyadh.